Support and services

Support Office for Aerogeophysical Research (SOAR): West antarctic field activities (1994–1996)

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Airborne research platforms are well suited to the study of Earth processes in remote regions. The mission of the Support Office for Aerogeophysical Research (SOAR), a facility of the National Science Foundation's Office of Polar Programs (NSF/OPP), is to make airborne geophysical observations available to the broad research community of geology, glaciology, and other sciences. The Institute for Geophysics at the University of Texas at Austin, Lamont-Doherty Earth Observatory of Columbia University, and the Geophysics Branch of the U.S. Geological Survey have the major responsibilities for SOAR. SOAR's central offices are located in Austin, Texas.

SOAR was chartered by a cooperative agreement between the National Science Foundation and the University of Texas at Austin. The facility goal is to develop, maintain, and operate a suite of geophysical systems aboard a Twin Otter aircraft for research in Antarctica. Much of the equipment, staff, and experience for SOAR were drawn from the Corridor Aerogeophysics of the Eastern Ross Transect Zone (CASERTZ) science project which developed this capability for the Twin Otter (Behrendt et al. 1994; Bell et al. 1993, pp. 571–577; Blankenship et al. 1993; Brozena et al. 1993).

The SOAR research aircraft provides a unique platform for the simultaneous collection of geophysical and navigation data. The geophysical instrumentation includes a gravimeter, magnetometer, laser altimeter, and ice-penetrating radar. The positioning instrumentation consists of single-frequency global positioning system (GPS) receivers for navigation, dual-frequency GPS receivers for postprocessed positioning (allowing differential carrier phase positioning), an inertial navigation system for aircraft attitude, and a precision pressure altimeter (table). The survey aircraft is a De Havilland DHC-6 Twin Otter modified to accommodate the geophysical and navigational equipment. The most visible modifications are large wing-mounted radar antennas below the wings and the towed magnetometer sensor "bird" stowed below the aft fuselage (figure 1).

Along with the hardware suite, robust data-acquisition and quality-control systems have been developed by SOAR. Measurements from each geophysical system are tagged with GPS time and recorded to disk. Continuous GPS positioning data are collected independently of the main acquisition system throughout each flight. Ground-based instrumentation collects magnetics observations and information on the GPS constellation. Data from each flight are downloaded and

Summary of geophysical and navigation equipment carried aboard the SOAR aircraft during the 1994–1996 field seasons

Equipment	Specifications
Gravimeter	Modified Bell BGM-3 gravimeter Gyro-stabilized accelerometer Damping circuitry modified for airborne use Track-line sampling distance approximately 70 meters Precision of a few milligals
Magnetometer	Proton-precession magnetometer Towed 30 meters below aircraft Track-line sampling distance approximately 100 meters Better than 1 nanotesla precision
Ice penetrating radar	Pulsed, 60-megahertz ice-penetrating radar 10 kilowatts peak power 2,000 digitized sweeps stacked Track-line sampling distance approximately 20 meters
Laser altimeter	Diode-pumped YAG laser 1.7 kilowatts peak power Operating limit in excess of 1,500 meters Single pulse accuracy approximately 0.1 meter Track-line sampling distance approximately 8 meters Surface elevations repeatable to within 0.25 meter when combined with GPS data
Navigational systems	Carrier-phase differential GPS Laser-gyro inertial navigation system Precision pressure altimeter Combined system resolution of approximately 0.1 meter

quality checked within a few hours of landing, allowing detection and correction of equipment malfunctions with minimal disruption to the survey schedule.

As an NSF facility, SOAR's fundamental goal is to meet the experimental objectives of its client science projects. Presently, SOAR has two clients working under separate proposals: a collaborative West Antarctic Ice Sheet Project and the University of Wisconsin–Madison. The science objectives of these researchers require SOAR to complete an aerogeophysical survey of a 200,000-square-kilometer region with an orthogonal survey grid and a 5.3-kilometer line spacing. This work started during the 1994–1995 antarctic summer field season and will be completed in the 1996–1997 season. Ultimately, three adjacent regions are to be covered (figure 2):

- the divide of the west antarctic ice sheet that overlies the Byrd Subglacial Basin (BSB on figure 2),
- the onset of ice stream D that overlies the lithospheric accommodation zone between the Byrd Subglacial Basin and the interior Ross embayment (WAZ on figure 2), and
- the trunk of ice stream D in the interior Ross embayment (TKD on figure 2).

For the 1994–1995 and 1995–1996 seasons, SOAR was based at Byrd Surface Camp. During these two seasons, the surveys of the BSB and WAZ were completed with a total of 120 survey flights gathering 67,000 line-kilometers of data. During its first field season, SOAR completed 32 survey flights in BSB. The second season (1995–1996) was much more ambitious, and 88 survey flights were completed. For 1995–1996, the sustainable rate for typical 4-hour survey flights

Figure 1. The SOAR aircraft configured for survey operations. Note the radar antenna under each wing and the towed magnetic sensor stowed underneath the tail of the aircraft.

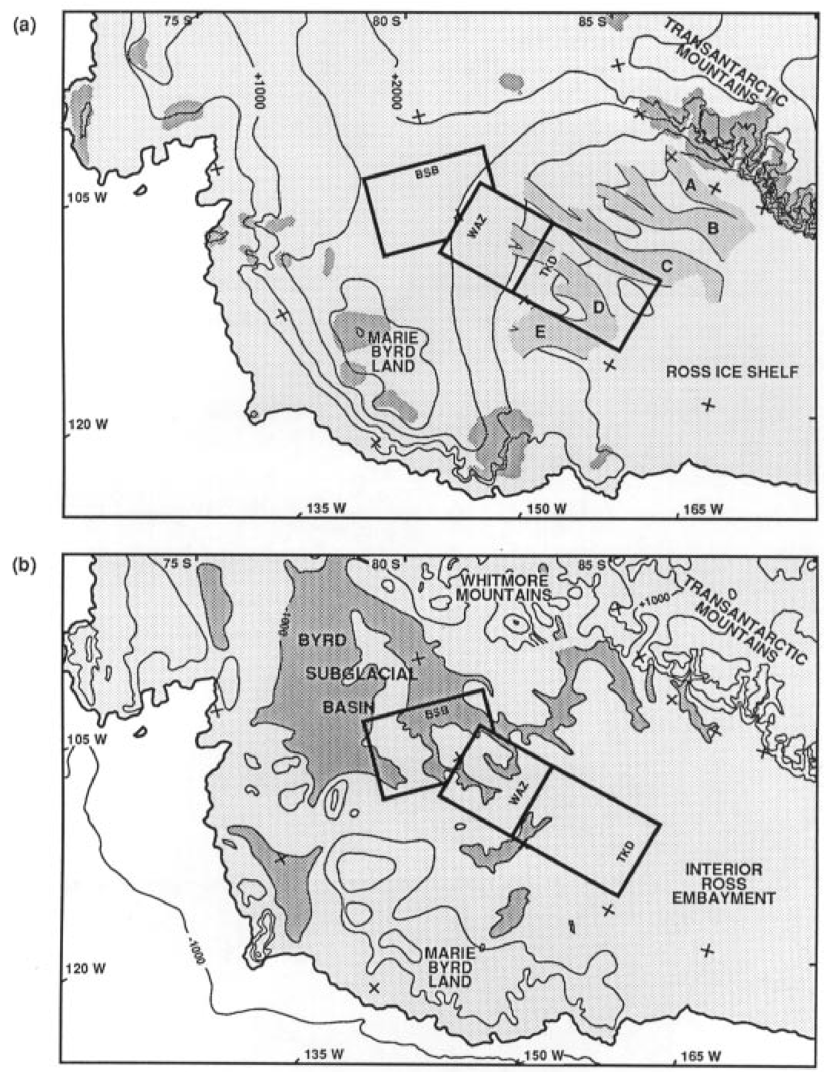

Figure 2. SOAR survey areas for the 1994–1996 field seasons shown on surface and bedrock topography of central West Antarctica (South Pole at upper right corner). The three targets are outlined with blocks: Byrd Subglacial Basin (BSB), the Whitmore Accommodation Zone (WAZ), and the trunk of ice stream D (TKD). *A*. Survey areas on the ice surface map. *B.* Survey areas on the bedrock topography map.

was 2.5 to 3.0 flights per day with approximately 1 day of bad weather every 3 days. During this season, SOAR maintained around-the-clock flight operations with one scheduled break per day to avoid collecting magnetics data during the worst of the diurnal geomagnetic field instabilities. GPS satellite visibility was good all of the time and did not pose a constraint on flight scheduling. For 1996–1997, the SOAR base-of-operations will be Siple Dome Camp. Seventy-two survey flights are planned to complete the West Antarctic Ice Sheet and University of Wisconsin Projects.

Following each field season, the data for the year are organized and distributed to the client investigators. Currently, the data provided are raw, unprocessed instrument readings with time stamps. Starting with the 1997–1998 field season, SOAR will begin to provide various levels of processed products.

The SOAR facility has large and diverse logistical requirements and was assisted by individuals and organizations in its field preparations and deployments. Operation and maintenance of the Twin Otter survey aircraft were provided by Kenn Borek Air, Ltd., through a contractual agreement managed by Antarctic Support Associates (ASA). ASA and the Naval Support Force Antarctica (NSFA) provided on-site management and support at Byrd Surface Camp. The Bell BGM-3 airborne gravimeter was on loan from the Naval Oceanographic Office. GPS receivers were supplied by the University Navigation Consortium (UNAVCO) and the National Aeronautics and Space Administration. Cargo support was provided by a number of groups and was coordinated by Lee Degalen for the NSF at Port Hueneme, California. SOAR would like to recognize the invaluable contributions to its success by these persons and organizations.

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Undergraduate research initiative: Antarctic marine geology and geophysics

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A new initiative for undergraduate research in Antarctica was begun in 1996 with the establishment of a Research Experience for Undergraduates (REU) site at Hamilton College. Although undergraduate participation in antarctic fieldwork and research has been conducted for a number of years, no formal organization of undergraduate participation was in place outside of those institutions that normally conduct antarctic science. The purpose of this program was to allow undergraduate students from institutions across the country to become involved in antarctic scientific work aboard U.S. Antarctic Program vessels.

The program began with national advertisement in *EOS, Transactions of the American Geophysical Union* and a mailing to all geology departments in the country. Approximately, 100 letters of interest were entertained and, of these, about 50 resulted in applications for participation. Students were selected based on letters of support, academic standing, and willingness of a home institution sponsor to coordinate the student research. Students were matched with principal investigators from those programs that were awarded National Science Foundation, Office of Polar Programs, grants to work on U.S. Antarctic Program vessels (table). Available space, research needs, and student background were all important considerations in selecting students. Six students were selected for the 1995–1996 field season and two students were selected for the 1996–1997 season (table).

All students (figure 1) participated in a week-long seminar at Hamilton College that was taught with help from Matt Kirby (a past REU participant who now teaches science at Canisius High School, Buffalo, New York), Scott Ishman (U.S. Geological Survey, Reston, Virginia), and Stephanie Shipp (Rice University, Houston, Texas). During the seminar, REU students were given a chance to learn about the antarctic region through discussions and exercises on geography, oceanography, marine geology, glaciology, meteorology, and paleoclimate (figure 2). This program followed the outline of a similar course that has been offered at Hamilton College since 1987. Logistical information was also reviewed at this time, and students were given some preliminary information on their cruise objectives, methodologies, and expected shipboard behavior.

Figure 1. REU students and instructors at Hamilton College, August 1995. Left to right, Matt Kirby (Canisius High School, New York), Melissa Feldburg (Wesleyan University, Connecticut), Matt LoPiccolo (Hamilton College), Seth Haines (Middlebury College), Eugene Domack, Koreen Mielke (University of Wisconsin–Oshkosh), Amelia Shevenell (Hamilton College), and Karl Anderson (University of Massachusetts).

Figure 2. Classroom instruction at Hamilton College prior to antarctic field season, assisted by Stephanie Shipp (far right).

Undergraduate participants in 1995–1996 and 1996–1997 antarctic field seasons

Student	Sponsor	Principal investigator/cruise	Home institution
1995–1996 field season			
Matt LoPiccolo	E. Domack	D. Karl/*Polar Duke*	Hamilton College
Seth Haines	P. Manley	L. Bartek/*Palmer*	Middlebury College
Koreen Mielke	W. Mode	L. Bartek/*Palmer*	University of Wisconsin-Oshkosh
Melissa Feldburg	S. O'Connell	S. Cande/*Palmer*	Wesleyan University
Karl Anderson	E. Cobabe	S. Cande/*Palmer*	University of Massachusetts
Amelia Shevenell	E. Domack	L. Lawver/*Palmer*	Hamilton College
1996–1997 field season			
Erik Jacobsen	E. Domack	R. Dunbar/*Palmer*	Hamilton College
Ward Lyles	P. Manley	S. Cande/*Palmer*	Middlebury College

Cruises took place aboard the R/V *Polar Duke* and R/V *Nathaniel B. Palmer* (table) across regions that varied from the Bransfield Strait (L. Lawver) to the Ross Sea (L. Bartek). Postcruise research took place at the home institutions and involved data collected during the cruise or previously collected marine geologic data. Projects ranged from multibeam imaging of seamounts in the Amundsen Sea (M. Feldburg) to paleoclimate records in glacial marine sediments of the Antarctic Peninsula (A. Shevenell). Early indications are that the program was a great success due in large part to the cooperation between principal investigators, home sponsors, and the support staff at Antarctic Support Associates. Preliminary publications are listed at the end of this article.

This program was supported by National Science Foundation grant OPP 94-18153 to Hamilton College. We acknowledge the support of the principal investigators (Steve Cande, Lou Bartek, Larry Lawver, Dave Karl, and R. Dunbar) and home institution sponsors (Patricia Manley, William Mode, Suzanne O'Connell, and Emily Cobabe).

Publications resulting from this program

LoPiccolo, M. 1996. Productivity meltwater cycles in Andvord Bay, Antarctica: Evidence of high frequency paleoclimatic fluctuations. (B.A. thesis, Hamilton College, Clinton, New York.)

LoPiccolo, M. In preparation. Productivity and meltwater cycles in Andvord Bay, Antarctica. *Sedimentology*.

Shevenell, A.E. 1996. Record of Holocene paleoclimatic change along the Antarctic Peninsula: Evidence from glacial marine sediments, Lallemand Fjord. (B.A. thesis, Hamilton College, Clinton, New York.)

Shevenell, A.E., and E.W. Domack. In preparation. Record of Holocene paleoclimatic change along the Antarctic Peninsula: Evidence from glacial marine sediments, Lallemand Fjord. In M. Banks and M.J. Brown (Eds.), *Climate of the Southern Hemisphere* (Special publication). Tasmania: Royal Society of Tasmania.

Shevenell, A.E., M. LoPiccolo, B.T. Straten, and E.W. Domack. 1996. Holocene paleoenvironmental studies within antarctic fjords along the western side of the Antarctic Peninsula. In *Understanding hypsithermal and neoglacial fluctuations*, Northeast Geological Society of America meeting, abstracts with programs.

Straten, B.T. 1996. Evidence for gravity flows as sediment transport systems from high resolution seismic reflection data and piston cores taken from Admiralty Bay, King George Island, Antarctica. (B.A. thesis, Hamilton College, Clinton, New York.)

The geodesy and mapping program of the United States in Antarctica

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The National Science Foundation (NSF) through the U.S. Geological Survey (USGS) supports geodesy and mapping in Antarctica. During the 1995–1996 season, the USGS directed its antarctic geodesy and mapping program toward management of the global positioning system (GPS) base station at McMurdo, the establishment of GPS geodetic control, topographic and satellite image mapping, seismology, management of the Scientific Committee on Antarctic Research (SCAR) Library for Geodesy and Geographic Information, and the publication of a new antarctic gazetteer.

The USGS continued its management of the International GPS Geodynamics Service (IGS) geodetic station at McMurdo station. The station, named MCM4, is located at the Radarsat facility. A Turbo Rogue 8000 receiver capable of obtaining centimeter-level positional accuracy is operated at the station. The data support activities such as improving and extending the International Earth Rotation Service Terrestrial Reference Frame, monitoring deformation of the solid Earth, variations in sea level, ice sheets, and monitoring the ionosphere.

The USGS participated in the SCAR Epoch 96 continent-wide GPS campaign conducted between 20 January and 10 February 1996. The campaign connected antarctic GPS geodetic stations to stations on other continents as part of a geodetic network for geodynamics investigations. Also, the campaign connected rock-based stations to the global International Terrestrial Reference Frame. During the campaign, the USGS operated GPS stations at McMurdo Station and Amundsen–Scott South Pole Station. These geodetic data will be used to study geodynamics affecting the Antarctic and adjoining tectonic plates.

The USGS's geodetic field crew established geodetic control in the Shackleton Glacier area. The geodetic control will be used to support large-scale mapping of Vinson Massif and Bennett Platform. Also, USGS conducted geodetic surveys on Ross Island, White Island, Cape Roberts, and Marble Point and to the tide gauge at Cape Roberts. This geodetic network will assist in defining a sea-level tide datum for the McMurdo Sound area.

In January 1995, USGS surveyors conducted a geodetic survey to establish the position of the true South Pole (geodetic marker) at Amundsen–Scott South Pole Station. Using this season's observations and data from previous surveys, it has been determined that the ice sheet at the South Pole moves 9.98 meters per year in a northwesterly direction. The team installed a permanent brass marker identifying the 1995–1996 austral summer position.

Cheryl Hallam managed the digital cartography and geographic information system (GIS) program at McMurdo Station during the summer season. The program provided assistance to the automatic geophysical observations project, long-duration balloon program, the ecology and physiology of sea-ice brine microalgae, South Pole inland traverse, and the long-term ecological research project. Researchers' data were incorporated into a digital database where they became available for integration using GIS analysis.

The USGS's mapping program includes 1:50,000-scale topographic maps for areas in the McMurdo Dry Valleys. The mapping is being conducted in cooperation with the Land Information New Zealand. Under this cooperative program, the USGS obtains the aerial photographs, establishes the geodetic control, and performs the aerotriangulation. New Zealand performs the stereocompilation, collects digital cartographic data, prepares the shaded relief data, and provides color separates. The USGS will print the maps. The maps cover the Taylor and Wright Valleys, the Convoy Range, and Royal Society Range in the McMurdo Dry Valleys area. These 1:50,000-scale, 15-minute topographic maps have 50-meter contour intervals and 25-meter supplemental contours. The maps will include existing and new place names approved by the U.S. Board on Geographic Names (BGN). Five maps covering part of the Royal Society Range were published in August 1993 and seven additional maps will be published in 1997.

The USGS published the second version of the advanced very-high-resolution radiometer digital image map of Antarctica at 1:5,000,000 scale. This version contains contour data, permanent station locations, and BGN place names. This map was printed in July 1996. Also, a large-scale photomap of McMurdo Station was published in November 1995.

The USGS's South Pole seismic program continued operation during the 1996 austral winter season. The seismic station serves as a key station in the Worldwide Standardized Seismograph Network. These data are used by the USGS National Earthquake Information Center to help locate earthquake epicenters and origin times for seismic wave propagation.

The USGS manages the SCAR geodesy and geographic information library for the U.S. Antarctic Program. The library is the official depository and distribution point for antarctic photographic and cartographic products produced by the United States. The library has approximately 450,000 black-and-white and color aerial photographs of the Antarctic dating from Operation Highjump (1946–1947) through the 1995 field season. The library also houses geodetic control records, satellite images, maps, charts, and publications. These maps, charts, and publications are exchanged with other nations under the provisions of the Antarctic Treaty.

A new edition of the U.S. antarctic gazetteer, *Geographic Names of the Antarctic*, containing approximately 13,000 official decisions of the BGN was published in November 1995. It was compiled and edited by Fred G. Alberts. The gazetteer catalogs decisions made through 1994 in the same format as the 1980 edition, including name, geographical coordinates, descriptive text, and reason for naming. As in the 1980 edition, variant (unofficial) names will appear as cross-references to the official entry. All variant names will also be listed along with the related official name.

In parallel with publication as a textual reference, the information in the new gazetteer was converted to a digital database as part of the Geographic Names Information System (GNIS) of the United States. The digital file will be released in the near future to the Internet as a digital gazetteer with software for searching and analyzing the data.

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Subsurface soil temperature measurements at McMurdo Station, Antarctica

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Over the past 20 years as the U.S. antarctic research effort has expanded, McMurdo Station, the main U.S. facility in Antarctica, has grown in size and complexity. The increased activity at McMurdo has meant an increase in the introduction of hydrocarbon contaminants through fuel spills on the ice and soil around the station.

When considering movement of fuel spills in an area where the soil freezes intermittently (called the *active layer*) or has a permanently frozen layer (called *permafrost*), understanding the freeze-thaw patterns of the soil is essential. Freeze-thaw cycles greatly affect contaminant movement through the processes of exclusion and immobilization (Iskandar and Jenkins 1985; Zukowski, Tumeo, and Lilly 1989; Zukowski and Tumeo 1991; Tumeo and Davidson 1993).

Because soil temperatures in or around McMurdo Station have not been measured, the depth to permafrost or the nature of the active layer was not known. To gain this information, a string of thermistors was installed at the site of an accidental fuel release near the J-1 fuel storage tank at McMurdo. This article reports on the subsurface temperatures found at the spill site and their potential effects on contaminant migration. This project was part of a 3-year study to address fundamental questions that surround the analysis of hydrocarbon contamination movement in polar regions.

Site description and methodology

In mid-February 1991 during a transfer of fuel from tank J-2 to J-1, approximately 11,400 liters of JP-8 was spilled at a site located in the pass between McMurdo Station and Scott Station on Ross Island. In 1993, this spill site was selected as a study site to track the movement of the contaminant plume.

Grain size distribution (ASTM sieve method), percent organics (loss on ignition), and hydraulic conductivity (auger hole method) were used to characterize the soil conditions around the spill site. On 24 January 1994, a thermistor string was installed 120 centimeters (cm) into the ground near the spill to measure seasonal temperature changes in the soil subsurface. Before installation, each thermistor was calibrated to within ±0.3° of 0°C in an ice bath. During installation, ice-rich frozen ground was encountered at a depth of approximately 25 cm. Eight thermistors were mounted at the following depths from the soil surface: 10.2, 20.3, 30.5, 40.6, 61, 81.3, 101.6, and 121.9 cm. Temperature measurements have been taken weekly since the thermistors were installed.

Results

- *Soil characterization.* The soil around McMurdo and the spill site is basically crushed volcanic rock. Permeability and particle-size distribution indicate the soil is a silty-sand material with an average particle size of about 2 millimeters and a hydraulic conductivity of about 10^{-3} cm per second. Virtually no organic matter (less than 0.6 percent as measured by loss-on-ignition test) is present.

  The major source of smaller particles is human activity (heavy equipment used in the support of McMurdo Station and related activities). Particle-size distributions for soil collected from the first 15-cm and from 115-cm indicate a poorly sorted, or well-graded, material. The surface soil is slightly more coarse than the deeper soil, consistent with the theory that the fines migrate downward with infiltrating surface water.
- *Soil temperature profiles.* The table contains the soil temperatures measured with depth at the spill site from January 1994 through July 1996 (30 months). The figure shows the temperature profile for the top 30.5 cm of the soil profile.

  The data collected to date indicate that the permafrost layer is approximately 10 cm below the surface. Cores taken in the area show that ice-rich permafrost occurs at 23.4 cm below the surface.

Soil temperatures measured at McMurdo Station, January 1994 through July 1996
NOTE: nd denotes no data.

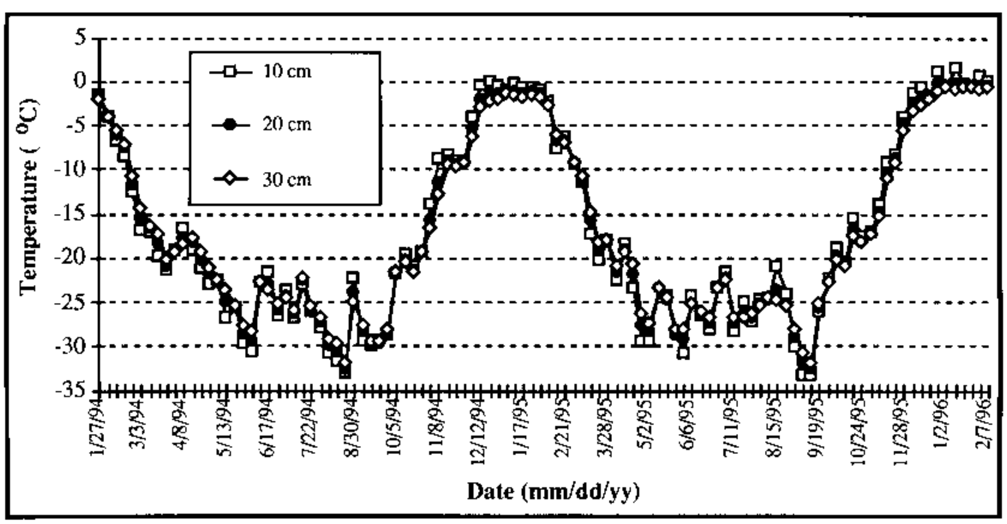
Date (d/m/y)	Depth (cm)							
	10.2	20.3	30.5	40.6	61.0	81.3	101.6	121.9
01/27/94	–1.6	–1.9	–2.2	–2.5	–3.0	–3.8	–4.5	–5.2
02/04/94	–4.0	–4.1	–4.0	–4.1	–4.2	–4.7	–5.3	–5.8
02/11/94	–6.7	–6.1	–5.7	–5.4	–5.1	–5.4	–5.8	–6.2
02/19/94	–8.5	–7.6	–7.2	–6.7	–6.5	–6.7	–7.0	–7.1
02/25/94	–12.6	–11.6	–10.9	–10.3	–9.1	–8.9	–8.7	–8.4
03/03/94	–16.9	–15.5	–14.4	–13.6	–12.4	–11.5	–10.9	–10.4
03/11/94	–17.1	–16.7	–16.4	–16.1	–15.2	–14.5	–13.8	–13.1
03/18/94	–19.7	–18.4	–17.4	–16.7	–15.5	–14.8	–14.3	–13.9
03/25/94	–21.3	–20.8	–20.3	–19.8	–18.6	–17.5	–16.6	–15.8
04/01/94	–19.2	–19.5	–19.4	–19.3	–18.7	–18.0	–17.4	–16.8
04/08/94	–16.6	–17.9	–18.4	–18.6	–18.4	–17.9	–17.5	–17.0
04/15/94	–19.1	–18.3	–17.7	–17.4	–16.8	–16.6	–16.5	–16.3
04/22/94	–21.3	–20.3	–19.5	–18.8	–17.9	–17.4	–17.1	–16.8
04/29/94	–22.9	–21.9	–21.1	–20.6	–19.6	–19.0	–18.6	–18.1
05/06/94	–22.6	–22.7	–22.5	–22.3	–21.5	–20.8	–20.1	–19.5
05/13/94	–26.8	–25.0	–23.7	–22.8	–21.6	–20.9	–20.4	–19.9
05/21/94	–25.7	–25.7	–25.5	–25.3	–24.5	–23.8	–22.9	–22.2
05/31/94	–29.6	–28.6	–27.8	–27.1	–26.0	–25.1	–24.3	–23.6
06/03/94	–30.6	–29.4	–28.4	–27.7	–26.5	–25.5	–24.8	–24.0
06/10/94	–22.8	–22.8	–22.8	–23.0	–23.2	–23.5	–23.5	–23.3
06/17/94	–21.7	–23.0	–23.6	–24.1	–24.2	–24.0	–23.7	–23.2
06/24/94	–26.6	–25.8	–25.1	–24.6	–23.7	–23.1	–22.7	–22.4
07/02/94	–23.7	–24.3	–24.5	–24.6	–24.3	–23.9	–23.5	–23.0
07/09/94	–26.9	–26.4	–25.9	–25.6	–25.0	–24.4	–24.0	–23.5
07/18/94	–23.0	–22.6	–22.3	–22.2	–22.1	–22.5	–22.9	–22.9
07/22/94	–26.0	–25.8	–25.3	–24.9	–24.1	–23.5	–23.2	–22.9
07/30/94	–27.9	–27.2	–26.7	–26.3	–25.6	–25.2	–24.7	–24.2
08/05/94	–30.9	–30.0	–29.3	–28.6	–27.3	–26.5	–25.8	–25.2
08/15/94	–31.8	–30.6	–29.6	–28.9	–27.7	–26.9	–26.4	–25.8
08/20/94	–33.1	–32.7	–32.0	–31.4	–30.2	–29.3	–28.5	–27.7
08/30/94	–22.2	–23.9	–24.9	–25.7	–26.6	–27.1	–27.3	–27.1
09/06/94	–29.6	–28.4	–27.6	–27.0	–26.1	–25.6	–25.4	–25.1
09/13/94	–30.0	–29.8	–29.4	–29.1	–28.2	–27.5	–27.0	–26.5
09/20/94	–29.3	–29.6	–29.6	–29.5	–28.9	–28.4	–27.9	–27.3
09/26/94	–28.8	–28.5	–28.2	–28.1	–27.8	–27.6	–27.3	–27.0
10/05/94	–21.8	–21.6	–21.5	–21.9	–22.6	–23.6	–24.4	–24.7
10/11/94	–19.6	–20.2	–20.5	–20.8	–21.2	–21.9	–22.4	–22.6
10/19/94	–20.9	–21.4	–21.6	–21.9	–22.2	–22.5	–22.8	–22.8
10/25/94	–19.4	–19.4	–19.4	–19.5	–19.9	–20.5	–21.1	–21.4
11/01/94	–14.0	–15.7	–16.6	–17.5	–18.4	–19.4	–20.0	–20.4
11/08/94	–8.9	–11.5	–12.8	–13.8	–14.9	–16.2	–17.3	–17.9
11/14/94	–8.3	–9.0	–9.5	–10.3	–11.7	–13.4	–14.8	–15.6
11/22/94	–9.0	–9.5	–9.7	–10.1	–10.6	–11.8	–12.9	–13.7
11/29/94	–9.0	–9.2	–9.3	–9.8	–10.6	–11.7	–12.7	–13.3
12/06/94	–4.1	–5.5	–6.2	–7.1	–8.3	–9.7	–10.9	–11.7
12/12/94	–0.6	–2.0	–3.0	–4.1	–5.8	–7.6	–9.0	–10.0
12/20/94	–0.1	–1.4	–2.2	–3.0	–4.5	–6.1	–7.6	–8.5
12/27/94	–0.6	–1.4	–2.0	–2.8	–4.0	–5.5	–6.7	–7.7

Soil temperatures measured at McMurdo Station, January 1994 through July 1996 (Continued)
NOTE: nd denotes no data.

Date (d/m/y)	Depth (cm)							
	10.2	20.3	30.5	40.6	61.0	81.3	101.6	121.9
01/03/95	–0.9	–1.0	–1.5	–2.2	–3.4	–4.8	–6.1	–7.0
01/10/95	–0.2	–1.1	–1.7	–2.4	–3.3	–4.6	–5.6	–6.4
01/17/95	–0.7	–1.4	–1.8	–2.3	–3.1	–4.3	–5.3	–6.0
01/23/95	–0.8	–1.3	–1.7	–2.2	–3.0	–4.1	–5.1	–5.7
01/31/95	–1.0	–1.4	–1.8	–2.3	–2.9	–4.0	–4.8	–5.5
02/06/95	–2.3	–2.6	–2.7	–3.0	–3.2	–4.0	–4.8	–5.3
02/14/95	–7.7	–6.8	–6.1	–4.8	–5.1	–5.2	–5.5	–5.7
02/21/95	–6.2	–6.9	–7.0	–7.1	–7.0	–7.0	–7.1	–7.0
02/28/95	–9.5	–9.5	–9.2	–8.8	–7.9	–7.5	–7.4	–7.4
03/07/95	–11.6	–11.2	–10.8	–10.5	–9.8	–9.4	–9.1	–8.9
03/14/95	–17.2	–15.8	–14.8	–14.1	–12.8	–16.0	–11.2	–10.6
03/21/95	–20.2	–19.1	–18.1	–17.3	–15.7	–14.5	–13.7	–13.0
03/28/95	–18.0	–18.1	–17.9	–17.8	–17.1	–16.5	–15.9	–15.2
04/04/95	–22.6	–21.6	–20.8	–20.1	–18.9	–18.0	–17.3	–16.5
04/12/95	–18.4	–19.1	–19.4	–19.6	–19.5	–19.2	–18.7	–18.1
04/18/95	–23.3	–21.8	–20.8	–20.0	–18.9	–18.2	–17.8	–17.4
04/25/95	–29.5	–27.6	–26.3	–25.2	–23.4	–21.9	–20.7	–19.7
05/02/95	–29.5	–28.5	–27.5	–26.6	–25.1	–23.8	–22.8	–21.9
05/08/95	nd	–23.4	–23.4	–23.4	–23.1	–22.9	–22.6	–22.1
05/16/95	–24.2	–24.7	–24.5	–24.2	–23.4	–22.8	–22.3	–21.8
05/23/95	nd	–28.8	–28.1	–27.5	–26.1	–24.9	–24.0	–23.4
05/31/95	–30.8	–29.2	–28.1	–27.3	–25.9	–24.9	–24.2	–23.6
06/06/95	–24.2	nd	–25.3	–25.6	–25.8	–25.5	–25.1	–24.6
06/13/95	–26.5	–26.3	–26.1	–25.9	–25.5	–25.2	–24.8	–24.2
06/20/95	–28.1	–27.5	–26.8	–26.2	–25.2	–24.6	–24.1	–23.7
06/27/95	–23.5	–23.4	–23.3	–23.4	–23.5	–23.7	–23.8	–23.6
07/04/95	–21.7	–22.2	–22.4	–22.6	–22.7	–22.8	–22.8	–22.7
07/11/95	–28.4	–27.6	–26.8	–26.2	–25.1	–24.2	–23.6	–23.1
07/18/95	–25.0	–26.4	–26.7	–26.8	–26.2	–25.6	–25.0	–24.4
07/25/95	–27.3	–26.9	–26.4	–26.1	–25.5	–25.0	–24.6	–24.2
08/01/95	–24.7	–25.2	–25.3	–25.5	–25.6	–25.5	–25.3	–24.9
08/08/95	–24.5	–24.7	–24.6	–24.7	–24.7	–24.7	–24.7	–24.5
08/15/95	–20.9	–23.5	–24.7	–25.5	–25.8	–25.6	–25.2	–24.8
08/22/95	–24.1	–25.2	–25.5	–25.6	–25.2	–24.9	–24.6	–24.2
08/29/95	–30.1	–29.0	–28.1	–27.4	–26.2	–25.3	–24.7	–24.3
09/05/95	–33.2	–31.9	–30.8	–29.9	–28.5	–27.4	–26.6	–25.9
09/12/95	–33.2	–32.7	–32.0	–31.3	–30.0	–28.9	–28.1	–27.4
09/19/95	–26.0	–25.6	–25.3	–25.2	–25.0	–25.1	–25.3	–25.3
09/26/95	–22.2	–22.6	–22.8	–23.0	–23.1	–23.6	–24.0	–24.1
10/03/95	–18.9	–19.7	–20.2	–20.7	–21.5	–22.3	–22.8	–23.0
10/10/95	–20.5	–20.8	–20.8	–21.0	–21.2	–21.7	–22.0	–22.2
10/17/95	–15.6	–16.8	–17.6	–18.4	–19.5	–20.5	–21.2	–21.7
10/24/95	–17.6	–18.1	–18.3	–18.6	–18.9	–19.5	–20.0	–20.2
10/31/95	–17.1	–17.2	–17.3	–17.6	–18.0	–18.8	–19.3	–19.5
11/07/95	–14.0	–15.0	–15.4	–15.9	–16.5	–17.4	–18.2	–18.5
11/14/95	–9.2	–10.4	–11.1	–12.0	–13.4	–14.9	–16.1	–16.7
11/21/95	–8.4	–8.8	–9.3	–10.0	–11.3	–12.7	–13.9	–14.6
11/28/95	–4.1	–4.8	–5.6	–6.6	–8.3	–10.1	–11.6	–12.6
12/05/95	–1.4	–2.4	–3.3	–4.5	–6.1	–8.0	–9.5	–10.5
12/12/95	–0.8	–2.0	–2.7	–3.6	–5.0	–6.7	–8.2	–9.1
12/19/95	–1.7	–1.7	–2.1	–2.7	–4.0	–5.6	–7.0	–7.9
12/26/95	1.0	–0.2	–1.1	–2.0	–3.3	–4.9	–6.2	–7.2

Soil temperatures measured at McMurdo Station, January 1994 through July 1996 (Continued)
NOTE: nd denotes no data.

Date (d/m/y)	Depth (cm)							
	10.2	20.3	30.5	40.6	61.0	81.3	101.6	121.9
01/02/96	–0.6	–0.6	–0.7	–1.4	–2.6	–4.1	–5.5	–6.3
01/09/96	1.6	–0.2	–0.9	–1.5	–2.4	–3.7	–4.9	–5.7
01/16/96	–0.3	–0.4	–0.8	–1.3	–2.3	–3.6	–4.7	–5.4
01/23/96	–0.6	–0.5	–0.7	–1.2	–2.1	–3.3	–8.4	–5.1
01/31/96	0.7	–0.4	–0.8	–1.3	–2.0	–3.2	–4.1	–4.8
02/07/96	0.1	–0.4	–0.7	–1.2	–2.0	–3.1	–4.0	–4.6
02/13/96	–5.7	–4.0	–2.9	–2.4	–2.2	–3.0	–3.9	–4.5
02/20/96	–10.2	–8.8	–7.8	–7.1	–5.8	–5.1	–5.2	–5.3
02/27/96	–9.8	–9.9	–9.7	–9.4	–8.5	–7.9	–7.5	–7.1
03/05/96	–15.3	–13.8	–12.8	–12.1	–10.8	–9.8	–9.2	–8.8
03/12/96	–15.9	–14.5	–13.7	–13.1	–12.1	–11.5	nd	–10.7
03/19/96	–18.9	–16.4	–16.4	–15.7	–14.3	–13.4	–12.8	–12.5
03/26/96	–20.2	–18.6	–17.6	–16.9	–15.7	–14.9	–14.2	–13.7
04/02/96	–20.1	–19.7	–19.0	–18.3	–16.9	–16.1	–15.5	–15.0
04/09/96	–19.7	–19.4	–19.0	–18.7	–17.9	–17.3	–16.7	–16.1
04/16/96	–13.8	–14.8	–15.2	–15.5	–15.8	–16.0	–16.1	–15.9
04/23/96	–17.6	–17.3	–16.9	–16.7	–16.2	–15.9	–15.7	–15.4
04/30/96	–22.7	–21.0	–19.8	–22.5	–17.9	–17.1	–16.6	–16.2
05/07/96	–22.6	–21.2	–20.3	–19.5	–19.1	–18.1	–17.4	–16.5
05/14/96	–18.8	–18.5	–18.2	–18.1	–17.7	–17.6	–17.5	–17.4
05/21/96	–24.7	–23.3	–22.2	–21.5	–20.1	–19.2	–18.6	–18.1
05/27/96	–30.8	–28.8	–27.3	–26.2	–24.3	–22.9	–21.9	–21.1
06/04/96	–27.1	–26.9	–26.5	–26.1	–25.2	–24.2	–23.4	–22.6
06/11/96	–30.5	–29.1	–28.1	–27.5	–26.2	–25.1	–24.2	–23.4
06/18/96	–24.8	–24.7	–24.4	–24.2	–23.7	–23.5	–23.3	–23.0
06/25/96	–21.3	–21.6	–21.7	–22.0	–22.3	–22.8	–22.8	–22.6
07/02/96	–22.2	–23.3	–23.6	–23.7	–23.3	–22.9	–22.5	–22.2
07/09/96	–29.9	–28.7	–27.5	–26.7	–25.2	–24.1	–23.4	–22.8
07/16/96	–23.2	–23.8	–23.9	–23.9	–23.6	–23.3	–23.1	–22.7
07/23/96	–27.7	–27.0	–26.4	–26.0	–25.3	–24.8	–24.4	–23.9
07/30/96	–30.2	–29.4	–28.7	–28.1	–26.8	–25.8	–25.1	–24.4



Soil temperatures with depth from 1994 to 1996.

Implications of data on contaminant movement

In ice-rich permafrost, the pores of the permanently frozen soil are filled with ice, thereby creating an effective barrier against downward migration of water and/or contaminants. The fact that the active layer is only approximately 10 cm deep, whereas ice-rich permafrost does not occur until 25 cm means that approximately 15 cm of frozen soil is not saturated, and contaminant can move freely through it. More important, the data indicate that there is probably not a zone of exclusion caused by freezing at the spill site. The fact that a zone of permanently frozen, non-saturated soil lies above the ice-rich zone means that the freezing front does not typically involve the freezing of pore water in the active layer. Instead, water will move downward into the permanently frozen non–ice-rich soil, and flow laterally across the top of the ice-rich layer, until it either freezes or exits the system through exfiltration or evaporation.

The one caveat to this conclusion is that if the water balance in the area is such that excess water is entering the system and adding to the ice-rich layer—in essence moving the ice-rich layer closer to the surface—a time may come when the active layer does have a saturated zone. In such an instance, exclusion could become an important factor in contaminant migration. In the arid climate of McMurdo, under normal circumstances there would probably not be enough excess water to result in an exclusion zone, but water is often applied into the roads in the summer months to control dust. In the future, this excess water conceivably could saturate areas of the active layer.

Acknowledgments

We would like to acknowledge the assistance and support of Antarctic Support Associates personnel for their consistent and conscientious monitoring of the thermistor string during two long antarctic winters. These dedicated individuals braved extreme cold to record the weekly readings from the thermistor string. Without their efforts, none of the information presented here would have been possible.

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The Amundsen–Scott South Pole Station water well: A new source of micrometeorites

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We have collected thousands of micrometeorites from the bottom of the Amundsen–Scott South Pole Station water well using a collector that we designed, built, and calibrated. The collector suctions and filters the particles on the ice surface as it traverses the well bottom. Preliminary results, based on two of the five samples returned, indicate that we may have the world's largest, best-dated, and best-preserved collection of micrometeorites. Also, because the area suctioned and the depositional age are known, further analysis of this collection will yield a measure of the terrestrial flux of 50–1,000-micron (μm) micrometeorites, the dominant mass contributors to the Earth. The micrometeorites we collected fell to Earth between 1100 and 1500 AD.

Micrometeorites are submillimeter, terrestrially collected extraterrestrial particles. Like meteorites, micrometeorites range from unaltered primordial materials to those that have seen extensive differentiation and alteration. They are the dominant mass contribution to the present-day Earth at about 100 tons each day (Love and Brownlee 1993). Although ubiquitous in terrestrial environments, micrometeorites are difficult to find and collect because they occur in low concentrations and generally weather rapidly. It is therefore necessary to find deposits where they are concentrated and preserved. Antarctica, with its cold climate and lack of terrestrial debris, is an excellent environment in which to look for micrometeorites.

The South Pole water well (SPWW) is a 24-meter (m) diameter by 16-m-deep melt pool 100 m below the snow surface at the South Pole (figure 1) and supplies drinking water for the Amundsen–Scott South Pole Station. The well was constructed during the 1992–1993 austral summer, and it has melted over 8,000 tons of firn and ice to date. A pump draws water from about 2 m below the water surface. About 10 percent of the water is consumed, and the rest is heated, using waste heat from the station, and returned to the well. This warm water melts more ice, and the well grows with time, primarily downward (i.e., through older ice). Micrometeorites that originally fell on the snow surface are liberated at the melting front and remain on the well bottom to form a lag deposit. The depositional age of these particles is known because the age of the ice is known as a function of depth (Kuivinen et al. 1982).

Our objective was to collect all 50–1,000-µm micrometeorites, without regard to density, shape, or magnetic susceptibility, from a large, known area of the well bottom. Our principal task was to build a collector that met strict operational requirements: it must not threaten water quality, it must descend through a 30-centimeter-diameter well neck and survive a cold soak at –50°C, and it must operate remotely in about 20 m of water at a distance of up to 200 m below the snow surface.

Our collector (figure 2) suctions and internally filters particles from the ice while traversing the well bottom. We control it from the surface via a waterproof electromechanical cable and use an underwater video system for visual feedback. The main body is a machined and folded sheet of low-density polyethylene that holds a polyester filter fabric (53-µm openings). When it is folded, a 2-millimeter-wide gap remains through which the pump draws water and entrained particles. The water flow is high enough (>1 meter per second) to entrain all particles, and the filter is immediately downstream of the intake slot to minimize particle damage and loss. A thin strip of polyethylene forms a check valve to seal the slot when the pump is off. A waterproof aluminum housing contains the pump, drive motors, and electrical connections. Spiked stainless steel wheels at opposite ends of the collector, powered by independent drive motors, move the collector around the bottom. The camera and light are suspended about 5 meters from the well floor by a split-out from the cable.

Prior to our deployment in December 1995, no information existed on the bottom topography of a water well. We found that the SPWW bottom had a gently curved central plateau (about 17 m^2) sculptured at its periphery into fairly steep arcuate dips that were 0.3–0.6 m below the plateau and 1–3 m wide (figure 3). These dips led to smaller plateaus (2–8 m^2). Associated with most sculptured features were visibly dark pockets of particulates, mostly iron-oxide grains derived from the water-supply system. On the plateau areas, particles were visible but not concentrated into pockets. The local surface was quite smooth (perhaps 1-millimeter depressions over 1–5-millimeter scales). Large circulation cells, established by the injected water and free convection along the walls, and local instabilities in these cells are probably responsible for the sculptured features.

During 2 weeks in December 1995, we deployed and retrieved the collector six times; as a result of this effort, we now have five filter bags (one filter was deployed twice) containing a total of about 200 grams of material. The collector maneuvered easily over the well's central plateau, and we devoted one collection (number 3) exclusively to it. We collected from five adjoining areas (about 10 m^2 total), including three particle pockets. Areas suctioned were visibly clean and indicate a high-efficiency particle pickup based on our laboratory experience (Taylor et al. in press).

We processed a pocket sample and the central-plateau sample in our field laboratory to assess the collector's performance. The material in the filters was backflushed into a stack of stainless steel sieves, using well water, and sorted into 53–106-µm, 106–250-µm, 250–425-µm, and more than 425-µm size fractions. Most of the materials in the samples were rust grains, derived from the well pump. Wood fragments and copper weld droplets were also found. To assess the meteoritic component, we removed all spherical particles from the 250–425-µm size fraction using a binocular microscope.

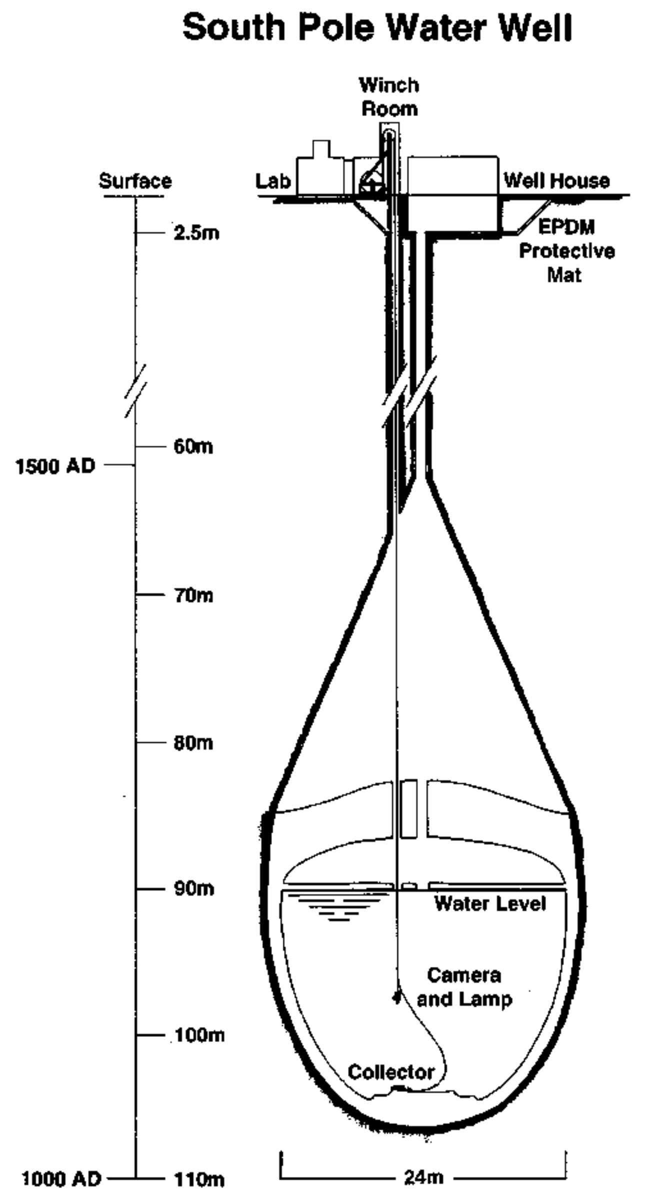

Figure 1. Approximate size and shape of the South Pole water well in December 1995.

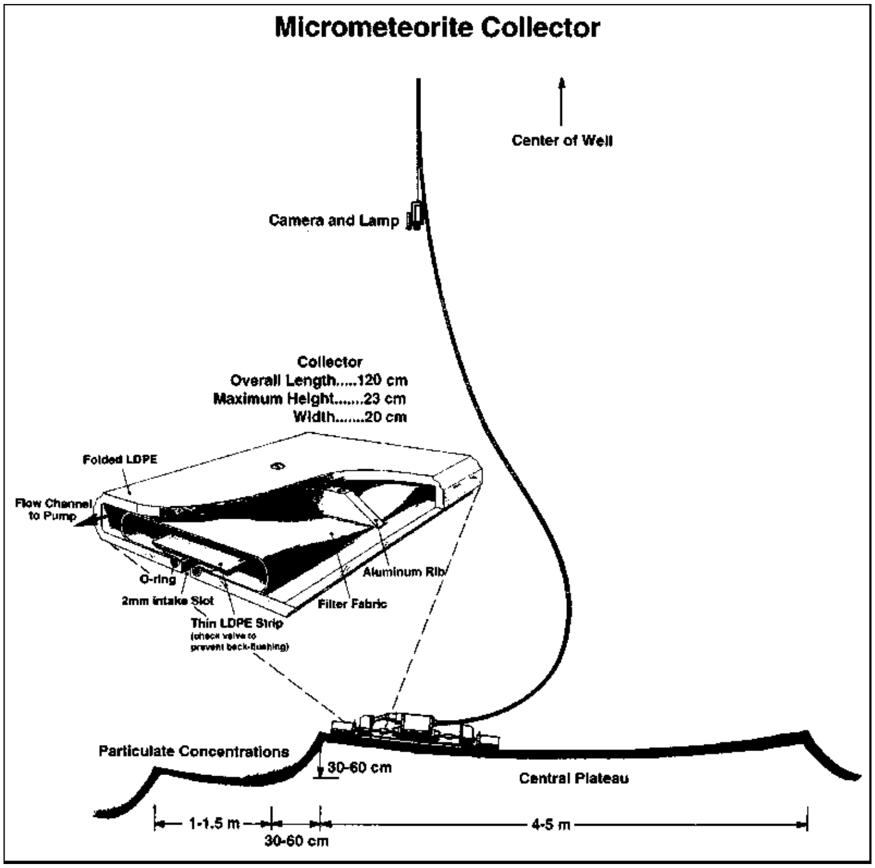

Figure 2. Schematic of collector and cross section of the collector arm. (LDPE denotes low-density polyethylene.)

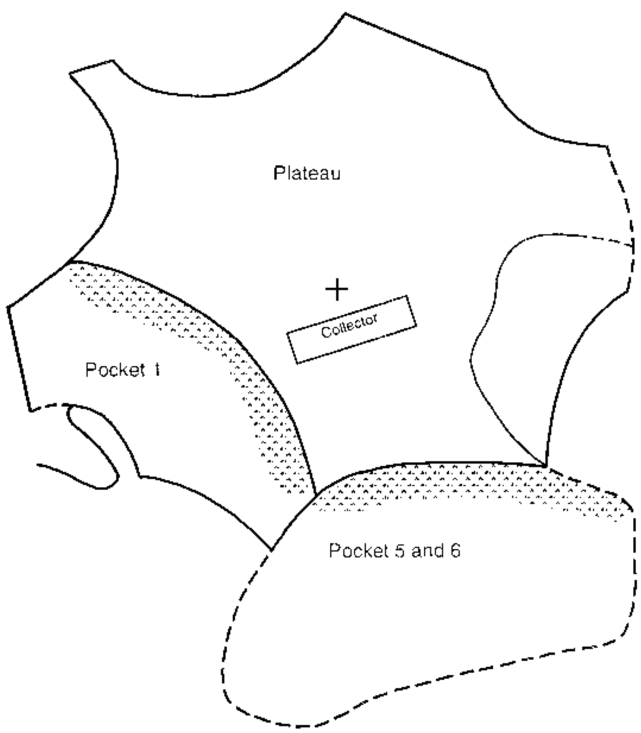

Figure 3. Plan view of the bottom of the South Pole water well. Slope changes are drawn in solid lines; dashed lines show areas we collected from but which were not imaged by the camera. The approximate locations of particle pockets are shown with stipples. The collector is 1.2 m long.

Cosmic spherules were then separated optically by their surface texture and color.

Upon our return to Hanover, New Hampshire, a subset of these spherules were mounted in epoxy and sectioned. Both their distinctive mineralogy and bulk chemistry indicate they are extraterrestrial. We found the full range of expected morphologies for cosmic spherules from glass spherules to unmelted particles. Silicate spherules having barred olivine textures are the most common type.

About 0.1 percent of the 250–425-μm size fraction of both samples examined were cosmic spherules. If this percentage represents the fraction of meteoritic material in all our samples, we will have about 0.2 grams of micrometeorites. For two reasons, however, we think this value is a minimum. First, we have not counted unmelted micrometeorites. These were abundant in the melted blue antarctic ice (Maurette et al. 1991), and we therefore expect to find many unmelted micrometeorites in our samples. Second, the melted meteoritic content was greater (0.2 percent) in a subsample of the 106–250-μm size fraction, the size fraction that also contains the largest total mass collected. Thus, the five SPWW samples should contain the world's largest collection of micrometeorites. The combination of a large number of micrometeorites of known depositional age makes the SPWW a unique and valuable source of micrometeorites.

We thank John Rand for his invaluable information about the well and Michael Shandrick of Antarctic Support Associates for assisting us at South Pole. This work was funded by the National Science Foundation grant OPP 93-16715; Julie Palais is our project monitor.

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Effects of tourism on the reproductive success of Adélie penguins at Palmer Station: Preliminary findings

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Tourism in Antarctica has increased significantly over the last 20 years, and predictions suggest this trend will continue (Enzenbacher 1994). The possibility that tourism may negatively affect wildlife populations has thus become an issue of increasing concern to both private and government organizations (Fraser and Trivelpiece 1994), and penguins have likewise become the focus of current efforts to understand interactions between humans and wildlife (Wilson, Taylor, and Barton 1990; Woehler et al. 1994; Fraser and Patterson 1996; Giese 1996). Long-term research undertaken at Palmer Station on Adélie penguins (*Pygoscelis adeliae*) was recently expanded to include a human-impacts component. Palmer Station is an ideal site for these studies because it is both a favored stop for tourists and the location of two programs that not only have a broad ecosystem perspective focused on the biology of Adélie penguins but also provide background ecological data (*see* Fraser and Patterson 1996). This article reports the preliminary results of one component of this study for the seasons 1993–1994 through 1995–1996, namely, the relationship between Adélie penguin breeding success and the incidence of visits by tourists.

Our study is based on Torgersen Island, which lies approximately 1 kilometer northwest of Palmer Station (figure 1). For several seasons, Torgersen Island has been divided into two areas, one open to tourism and the other closed; the latter serves as a control for conducting research in the former. Palmer Station receives approximately 12 ships per season (fewer than 1,300 tourists). Typical visits to Torgersen Island last about 4 hours, and a new group of 10–50 tourists arrives on the island every hour. We monitored tourist visits by censusing tourist numbers and noting their position relative to Adélie penguin colonies every 20 minutes. We then used these data to establish tourism flow profiles that allowed us to rank penguin colonies according to relative use (high, medium, and low) by tourists. Adélie penguin breeding success (number of chicks creched per pair) was determined by comparing breeding sample groups (BSGs) in tourist-visited and control sites. BSGs, each of which consisted of five nests, were randomly placed in colonies throughout the island and monitored daily to obtain data on egg laying, hatching, and chick survival. Between 150 and 200 nests equally divided between the two areas on Torgersen Island were studied each season.

The spatial distribution of tourists during the 3-year study is shown in figure 2. Tourism distribution exhibited a nonrandom pattern; some colonies received disproportionate amounts of activity. As figure 2 indicates, these patterns remained quite constant between years, suggesting that tourists visiting Torgersen Island tend to prefer (for reasons not yet determined) spending more time in some areas than in others.

Seasonal comparisons of the relationship between the number of tourist visits and Adélie penguin breeding success are summarized in the table. Reproductive success was compared using the student's *t*-test at an alpha level of 0.05. The three-season mean reproductive success for visited areas of

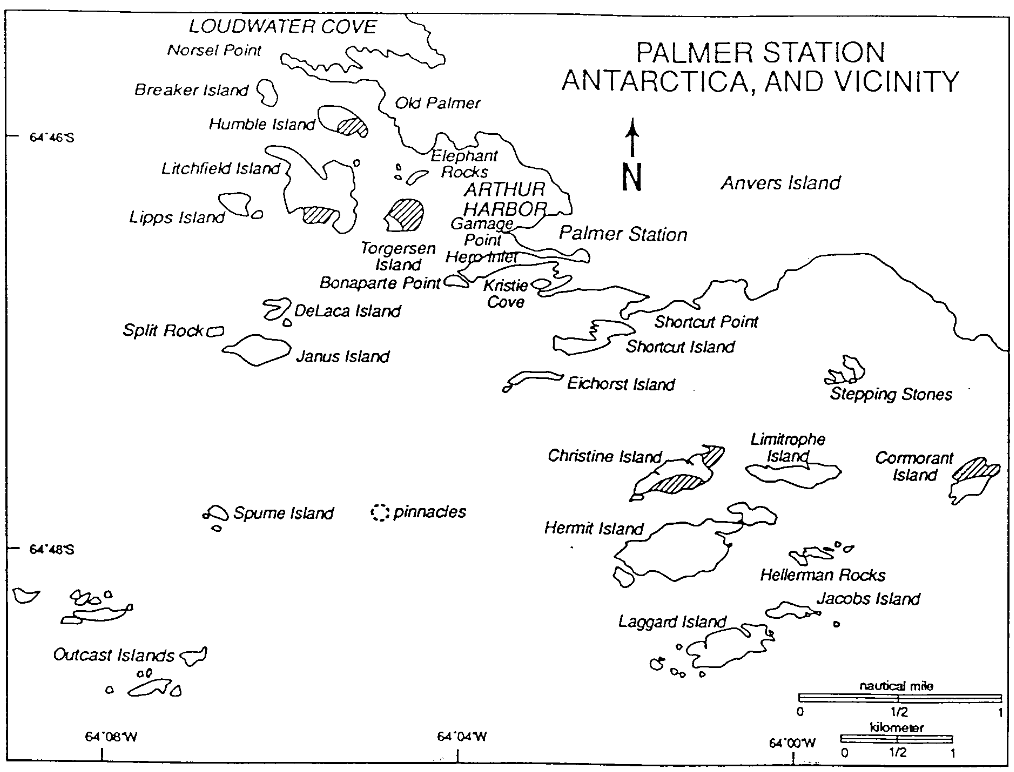

Figure 1. Palmer Station, Antarctica, and vicinity. Adélie penguin colonies on surrounding islands are indicated by shading.

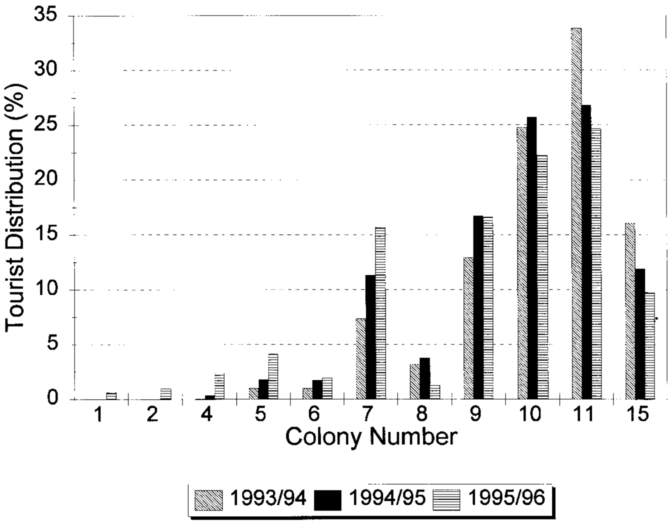

Figure 2. The spatial distribution of tourists on Torgersen Island in relation to Adélie penguin colony study sites, 1993–1994 through 1995–1996.

1.53±0.35 chicks creched per pair is significantly higher (t=2.00, df=89, p=0.049) than that for the control sites, where only 1.38±0.36 chicks were creched per pair. Although values for the 1995–1996 season suggest that a large increase in tourists (605 vs. 450 in 1994–1995) depressed reproductive success in the visited sites (1.56±0.28 vs. 1.47±0.38 chicks creched per pair, respectively), this is not the case. Further examination of the tourist-visited areas indicated that in high and medium use areas, mean productivity remained consistent (1.58±0.31 chicks creched per pair) with previous seasons. In the low use area, however, productivity dropped to only 1.08±0.36 chicks creched per pair thus depressing the overall mean for the visited sites.

Factors that potentially influence Adélie penguin reproductive success are numerous and complex (Reid 1968; Wilson et al. 1990; Fraser et al. 1992; Fraser and Trivelpiece 1994). Based on the preliminary evidence resulting from this study, it appears that tourism as it is currently regulated at Palmer Station does not affect Adélie penguin reproductive success. As such, our results diverge from those of Giese (1996) but support the hypothesis (cf. Fraser and Patterson 1996) that environmental factors associated with variability in the breeding habitat (i.e., snow deposition, colony aspect, predation) may be more influential in determining the fate of nesting Adélie penguins than tourism.

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Seasonal comparisons of Torgersen Island visits by tourists and Adélie penguin reproductive success (chicks creched per pair)

			Breeding sample groups			Reproductive success (mean ± standard deviation)		
Year	**Number of ships**	**Number of tourists**	**Tourist (n)**	**Control (n)**	**Total nests**	**Tourist sites**	**Control sites**	**Whole island**
1993–1994	6	400	15	15	150	1.55±0.44	1.27±0.54	1.41±0.51
1994–1995	5	450	25	15	200	1.56±0.28	1.39±0.22	1.47±0.27
1995–1996	9[a]	605	25	15	200	1.47±0.38	1.48±0.34	1.47±0.36
					Mean:	1.53±0.35	1.38±0.36	1.45±0.38

[a]Includes one Spanish naval ship which visited Torgersen Island on 9 December 1995 and two private yachts which landed eight passengers on 2 January 1996.